Tommaso TOFFOLI

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Research Affiliate
Boston University
Electrical and Computer Engineering

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Affiliate Member
formerly Principal Research Scientist (1977–1995)
Massachusetts Institute of Technology
Laboratory for Computer Science (now csail)

Curriculum Vitae
15 Oct 2020

IEEE Fellow, Oct 2012

PhD in Computer and Communication Sciences — The University of Michigan, Oct 1977
Doctor of Physics — University of Rome, Italy, Feb 1967

INTERESTS AND EXPERTISE. ACHIEVEMENTS

Information Mechanics. Foundations and physical aspects of computing. Theory of cellular automata. Interconnection complexity, synchronization. Formal models of computation consistent with microscopical physics (uniformity, locality, reversibility, inertia and other conservation principles, variational, relativistic, and quantum aspects of computation). Proved the computation-universality of invertible cellular automata (1977); formulated the conjecture (later proved by Kari) that all invertible cellular automata are structurally invertible (1990). Introduced the "Toffoli gate" (1981), which was later adopted by Feynman and others as a fundamental logic primitive for quantum computation. Proposed, with Fredkin, the first concrete charge-conserving scheme for computation (1980)—an idea that has been taken up by the low-power industry in recent years. Proved that dissipative cellular automata algorithms can be replaced by nondissipative lattice-gas algorithms (2006–2009). Advances in quantum information theory and thermodynamics (2006–2010).

Fungibility of bulk computation; connections between lagrangian action and computation capacity (1998–).

Fine-grained architectures for massively parallel computation. Pioneering work on cellular automata machines: design, realization, support, and applications (1982). Development and realization (with Norman Margolus) of cam8, a fine-grained, indefinitely scalable multiprocessor architecture which embodies the concept of *programmable matter* (1987–1993). Methodology for the use of these architectures in materials science simulations and in the exploration of a variety of parallel computation schemes. Design and realization of simp/step, a software engine and IDE for Programmable Matter, with Ted Bach (2002-04).

Connections between microscopic dynamical processes and macroscopic phenomenology. Discrete models of processes traditionally described in continuous terms; pioneered the idea of lattice-gas hydrodynamics (1985). Correspondence principles bewteen microscopic combinatorics and macroscopic computational properties; emergent computation. Physical modeling approaches that take advantage of massively parallel, fine-grained computational resources. Certain aspects of neural networks.

Image manipulation and three-dimensional rendering based on fine-grained autonomous dynamics (1995). Servoing of microscopic dynamics to pattern recognition: simulated staining, texture-locked loops.

Knowledge structuring. As part of an effort aimed at developing a Knowledge Engineering curriculum, created and taught a new graduate course, "Personal Knowledge Engineering" (2007-09). Collaborated with the BU Earlab on brain modeling project (2002–2008). Working (since 1998) on a broad initiative, called *Personal Knowledge Structuring*, which aims to make it possible for *ordinary* people to effectively use the computer to expand their *personal* capabilities—an extension of *literacy*. The strategy is to develop an integrated suite of cultural and computer resources and a pilot community for the support and dissemination of this discipline.

Brief curriculum

1961 BA, Liceo–Ginnasio VIRGILIO, Rome, Italy.

1965 Scholarship from National Health Institute, Rome, Italy: digital electronics, measurement, and measurement processing.

1967 Doctor of Physics, University of Rome, Italy, with a thesis on "A wide-angle directional detector of cosmic-ray muons, utilizing the Čerenkov effect."

1969 Fulbright–Hays scholarship. Research on self-replicating programs and structures, Case Institute of Technology.

1970 Research and PhD program in the Comp. Comm. Sci. Dept., The University of Michigan. Teaching Fellowships and Research Assistantships from said department.

1972 Five-year contract as Research Associate at the Institute for the Applications of Computation, National Research Council, Rome, Italy. Design methodology for computer models of large water-resource systems. Techniques for interactive model construction and treatment. Special-purpose compilers. Image processing in problems of landscape contour. Techniques for branch-and-bound optimization. Identification of optimal data structures for operations research problems.

1973 Translated and adapted Robert Gagné's book *Learning and Individual Differences*, Merrill 1967, for the Italian publisher Armando.

1975 Contract renewed for five years as Full Researcher. Structural manipulation of nonlinear optimization models. Consulting work for the School of Water Resources Management, Catania, Italy, and the Italian National Electricity Agency (ENEL).

1976 Resumed doctoral program at The University of Michigan. Research on uniform dynamical systems, cellular automata, reversible computation, and physical aspects of computation.

1977 PhD in Computer and Communication Science, The University Michigan, with a thesis on "Cellular Automata Mechanics."

1978 Research Associate at the MIT Laboratory for Computer Science. Reversible computation, conservative logic, semi-intelligent control.

1981 Organization of the seminal "Physics of Computation" conference," MIT Endicott House 1981.

1982 Design and construction of SQUARELAND, a high-performance cellular automata machine. Artificial intelligence techniques in robotics and control. Organization of the "First Information Mechanics Workshop," BVI.

1983 Design and construction of improved cellular automata machines (CAM2, CAM3, CAM4). Nondissipative computation in classical and quantum systems. Modeling of differential equations by combinatorial processes. Organization of an interdisciplinary workshop on "Cellular Automata," Los Alamos National Laboratories. Consulting for DEC and IBM.

1984 Physical modeling by cellular automata. Production of CAM5. Organization of the "Second Information Mechanics Workshop," BVI.

1985–86 Work on the generalization to an information mechanical context of physical concepts such as temperature, energy, and action. Design, development, and supervision of the commercial production of CAM6—a high-performance cellular automata machine intended as an integrated laboratory for cellular automata experimentation. Initial design of CAM7, a large three-dimensional cellular automata multiprocessor. Lattice-gas models of fluid dynamics.

1986 Principal Research Scientist at the MIT Laboratory for Computer Science. Book: *Cellular Automata Machines—A new environment for modeling* (with Norman Margolus). Organization of the "Cellular Automata '86" conference (with Charles Bennett and Stephen Wolfram).

1987–88 Theoretical work on statistical mechanics and relativity in a cellular-automaton context. Functional design of CAM8—a large cellular automata mutiprocessor for Tera-events/sec.

1989 Three-year contract with DARPA for the final design and construction of CAM8, in collaboration with Norman Margolus. System and chip design, simulation, and testing.

1992 First operational CAM8 units. Collaborations with various groups on applications of the CAM8 architecture (meteorology, real-time 3D image manipulation and rendering, digital simulation).

1993 Further work on CAM8 applications. New three-year contract with ARPA for research on "Nanoscale Parallel Computation." Organization (with Bennett, Penrose, and Zurek) of a "Quantum Computation" workshop.

1994 New three-year contract with ARPA on "CAM8: Moving Toward Ultimate Computation" (coPI with N Margolus). Development of general techniques for three-dimensional modeling in CAM8: (a) simulation of continuous, long-range forces by integration of impulses; (b) "space-time crystallography," or rational register-allocation criteria in discrete lattice models. Development of basic image-processing techniques in the CAM8 environment: optimal contrast enhancement, 3D rotations by shears. Organization of a second workshop on "Quantum Computation."

1995 Appointed Research Associate Professor in the Electrical, Computer and Systems Department, Boston University. Co-organizer of a third workshop on "Quantum Computation" (Turin, Jun 1995).

1996 General Chairman of the "Fourth Workshop on Physics and Computation," Boston University, 22–24 Nov 1996. Co-organizer of a fourth workshop on "Quantum Computation" (Turin, Jun 1997). Research in Programmable Matter (device physics, architectures, and software methodology aimed at exploiting atomic scale computational resources). A new course on "Hands-on embedded microcomputers."

1997 Started a research group on "Programmable Matter," with two graduate students, with partial support from a new grant from the Institute for Scientific Interchange, Turin, Italy and an older NSF grant. Contract with MIT Press for a book, *Introduction to Programmable Matter*. Co-organizer of a fifth workshop on "Quantum Computation" (Turin, Jun 1997).

1998 A new approach to the quantification of computational resources: *computation capacity* and its connections with Lagrangian action (a combinatorial justification of the variational principles of mechanics). Co-organizer of a sixth workshop on "Quantum Computation" (Turin, Jun 1998). Launch of the *Personal Knowledge Structuring* initiative with an invited address at the "History and culture in technology" conference in Turin, Italy. A number of pilot projects in this context.

1999 Exploration of concepts, contact, and fund-seeking for the knowledge structuring (personal and corporate) program. Design of a syllabus for a proposed course in Knowledge Structuring. First attempts to characterize a departmental effort in *knowledge engineering*.

2000 Appointed Associate Professor of Electrical and Computer Engineering. Cycle of lectures at ISI (Turin, Italy) on "Knowledge Structuring: The substance of Information Technology."

2001 Definition of the Knowledge Home initiative: motivation, approach, and agenda. Preparation for a charter workshop; probing and canvassing for interest and support. Further development of the SIMP/STEP integrated environment for cellular automata and lattice gas modeling.

2002 Organized and ran the charter workshop "Knowledge Home 2002," under the sponsorship of ISI, Turin, to publicly present the Knowledge Home initiative and gage its reception; collected consensus and offers of serious support. Started a collaboration with the Earlab Project (Biomedical Engineering), with the aim to contribute knowledge engineering expertise and discipline to the project.

2003 Work on the maximum speed of quantum gates, with L Levitin. Miniworkshop on the Knowledge Home in Trento, Italy. Designed a new graduate course, "Personal Knowledge Engineering."

2004 Teaching again the new course, now in the BU

catalog as SC726. Proposal writing in the Personal Knowledge Engineering area. Work on the foundations of quantum mechanics.

2005 Launch of the SIMP/STEP platform for cellular automata and lattice gases. Continuing collaboration with the Earlab project, with the goal to systematize and partially automate the classification of neurons and their interconnections, especially in the auditory system.

2006 Collaboration with Lev Levitin on the thermodynamics of computation. In collaboration with the University of Rome, advances on a problem concerning the replaceability of cellular automata algorithms by lattice-gas algorithms.

2007 Design of a "Spartan Environment," bypassing desktop burdens, for SC726. Thermodynamic cost of reversible computing.

2008 Breakthrough in translating conventional dissipative computational schemes into equivalent schemes that, while still needing a thermal sink, do not need more energy than that available in the input data.

2009 Integration of the Spartan Environment with Ubuntu and Latex. Proved, with Levitin, that the unified bound on the rate of quantum dynamics is tight.

2010 Introducing elements of Spartan Programming and Literate Documentation in SC726. An original paper on the origins of probability.

2011 Started work on a book, *Evolution Regained*, for Cambridge University Press, in collaboration with Prof. Gregg Jaeger.

2013 Collaboration with Prof. Roscoe Giles on the development of the EC440 Operating Systems course. Introduction to this course and to other BU projects of the RaspberryPi Linux board, as an operating system workbench and a general-purpose embedded computer for student projects. Continued writing the *Evolution Regained* book. Work on a more general definition of "entropy of a system" that fully satisfies the desiderata of information theory as well as of thermodynamics.

2014 Wrote a seminal (and gone viral) paper, "Entropy? Honest!" on the real nature of entropy and the second law of thermodynamics, among other things proving that *any dynamical system* (and so not necessarily physical) satisfies the second law *if and only if* its dynamics is *invertible*—no more and no less!

2017 to present Continuing working on the evolution book. Progress on identifying evolution in general (not only biological) as a manifestation of an *emergent system* that has entered a *runaway regime*, which for thermodynamical reasons must eventually end—with a fizzle or a bang. Also, as a challenge to the Artificial Life community, a paper, "Waiting for the rapture: what can we do with computers to (hopefully) witness the *emergence* of life? (*Natural Computing* conference, 2017.)

Scientific societies

1. IEEE Fellow.
2. Member of Sigma Xi, The Scientific Research Society of North America.
3. Member of the Mathematical Association of America.
4. Member of IEEE Computer Society.

Editorial and scientific boards

1. Member of the editorial board of *Journal of Quantum Information Science*.
2. Member of the editorial board of *Journal of Cellular Automata*.
3. Member of the editorial board of the journal *Complex Systems*.
4. Member of the editorial board of *International Journal of Unconventional Computing*.
5. Member of the editorial board of *Journal of Quantum Information Science*.

Research grants

2008	Share in a Biomedical Engineering grant	NIH	$56,000
2007	Share in a Biomedical Engineering grant	NIH	$56,000
2006	Share in a Biomedical Engineering grant	NIH	$56,000
2005	Share in a Biomedical Engineering grant	NIH	$56,000
2004	Share in a Biomedical Engineering grant	NIH	$56,000
2003	Share in a Biomedical Engineering grant	NIH	$53,000
2002	Share in a Biomedical Engineering grant	NIH	$53,000
2000	Personal Knowledge Structuring	ISI	$50,000
1999	Programmable Matter Methods	DOE	≈ $340,000
1999	Personal Knowledge Structuring	ISI	$14,000
1997	Paths to Programmable Matter	ISI	$25,000
1995–97	Information Mechanics	NSF	$180,000
1994	Nanoscale Parallel Computation	DARPA	$670,000
1992–95	CAM8 (Renewals and extensions, with N. Margolus)	DARPA	≈ $180,000
1989–91	CAM8: A Uniform, Scalable, General-Purpose Cellular Automata Architecture for Tera-events/sec	DARPA	$2,809,300
1987	Cellular automata algorithms	IBM	≈ $80,000
1983–85	Information Preserving Models of Physics and Computation	DOE	$330,000
1982–84	Information Preserving Dynamics	NSF	≈ $300,000
1980	Design principles for achieving high-performance submicron digital technologies (with E. Fredkin as PI)	DARPA	≈ $90,000

Patents and disclosures

1. "Three-dimensional interconnect having stacking modules with orthogonal geometry" (invention disclosure, 24 March 1997).
2. "Multidimensional Cellular Data Array Processing System which Separately Permutes Stored Data Elements and Applies Transformation Rules to Permuted Elements" (inventorship in the name of N. Margolus, rights to MIT, inventor's royalties to be shared between N. Margolus and T. Toffoli)
3. "A high-performance cellular automata machine" (licensing rights transferred to MIT in exchange for a more favorable royalty-sharing contract, 1986).

Teaching

Boston University

2012/13 EC440 Operating Systems (w/ Roscoe Giles)

2009/10 SC726 Personal Knowledge Engineering
EK130 Memorable experiments

2008/09 SC726 Personal Knowledge Engineering
EK130 Memorable experiments

2007/08 SC726 Personal Knowledge Engineering
EK130 Programming via Python

2006/07 SC726 Personal Knowledge Engineering
SC450 Microprocessors

2005/06 SC700 Personal Knowledge Eng. Projects
SC450 Microprocessors
EK130 Memorable experiments

2004/05 SC450 Microprocessors
EK130 Memorable experiments
SC910 Project (design of a hovercraft)

2003/04 SC726 Personal Knowledge Engineering
SC450 Microprocessors
EK130 Memorable experiments

2002/03 SC700 Personal Knowledge Engineering
SC450 Microprocessors

2001/02 SC700 How to make a computer language
SC450 Microprocessors

2000/01 SC450 Microprocessors

1997/98 SC451 Directed study
SC466 Senior Project

1996/97 EK130 Hands-on microcontrollers

Massachusetts Institute of Technology

1981 Information mechanics

1979 Structure and evaluation of computer programs.

1978 Introduction to microcomputers.

Institute for Scientific Interchange, Turin, Italy

2000 Cycle of lectures on "Knowledge Structuring: The substance of Information Technology."

Math. Department, University of Cosenza, Italy

1991 Fine-grain parallel computation (cycle of 10 seminars).

The University of Michigan

1976 Theory of automata.

1975 Found. computer and communication science.

1970, 1975 Introduction to computer programming.

School for water resources manag., Catania, Italy

1974 Introduction to Operations Research.

Students: MS and PhD advisees

1. Ahmad Katerji, achieved PhD in Fall 2008 with a thesis on the "Stuctured display of neurological database information."

2. Ted Bach, achieved PhD in 2006 with a thesis on "A rational framework for programmable matter."

3. Zac Walton, achieved a PhD in 2004 with a thesis on "Noise-immune entangled-photon quantum cryptography."

4. Silvio Capobianco, achieved PhD in Mathematics at the University of Rome "La Sapienza" in 2005. I had been his advisor since 2003, and had him as a Visiting Scientist at BU for a term in 2004. I still very actively collaborate with him.

5. Brian Rossa, left for employement with Lockheed–Martin in 2004 after one term in the PhD Program.

6. Morteza Navabi, achieved an MS in 2009.

7. Lan Hu, achieved an MS in 2003.

8. Lee Lichtenstein, achieved an MS in 2003.

Publications

Books

1. Toffoli, Tommaso, and Norman Margolus, *Cellular Automata Machines—A New Environment for Modeling*, MIT Press 1987; translated into Russian as *Mashiny Kletochnykh Avtomatov*, Izdatelstvo "Mir" 1991.
2. Califano, Andrea, Norman Margolus, and Tommaso Toffoli, *CAM6 User's Guide*, Automatrix, Inc., PO Box 196, Rexford, NY 12148-0196, 1987..

Proceedings editor

1. Toffoli, Tommaso, (ed.), *Digital Perspectives*, proceedings of an NSF (Washington) conference, special issue of *Int. J Theor. Phys.*, **42**:2 (Feb 2003).
2. Toffoli, Tommaso, and Michael Biafore (ed.), *Physics and Computation 1996*, North–Holland 1998.
3. Toffoli, Tommaso, Michael Biafore, and João Leão (eds.), *PhysComp96*, New England Complex Systems Institute 1996.
4. Gruska, Josef, Tommaso Toffoli, Hiroshi Umeo and Roland Vollmar (eds.), *Cellular Automata*, Dagstuhl–Seminar 9510, March 1995, Schloss Dagstuhl, Saarbrücken, Germany.
5. Bennett, Charles, Tommaso Toffoli, and Stephen Wolfram (eds.), "Cellular Automata '86 Conference," Tech. Memo MIT/LCS/TM-317, MIT Lab. for Comp. Sci. (December 1986), reprinted in *Complex Systems* **1**:1/2 (1987).
6. Farmer, Doyne, Tommaso Toffoli, and Stephen Wolfram (ed.), *Cellular Automata*, North–Holland 1984.
7. Landauer, Rolf, Edward Fredkin, and Tommaso Toffoli (eds.), *Physics of Computation*, proceedings of an MIT (Endicott House) conference, special issues of *Int. J Theor. Phys.*, **21**:3/4, **21**:6/7, and **21**:12 (1982).

Papers in refereed journals

1. Toffoli, Tommaso, 'Waiting for the rapture: what can we do with computers to (hopefully) witness the emergence of life?" *Natural Computing*, 42pp, in press (Oct 2017).
2. Toffoli, Tommaso, "Entropy? Honest!" *Entropy* **18**:7 (Jun 2016), 247.
3. Levitin, B Lev, and Tommaso Toffoli, "Heat-to-work conversion by exploiting pairwise correlations of quantum particles," *Int J Theor. Phys.* **50**:12 (Dec 2011), 3844–3851.
4. Capobianco, Silvio, and Tommaso Toffoli, "Can anything from Noether's theorem be salvaged for discrete dynamical systems?" in *Unconventional Computation 2011*, Springer (Lecture Notes in Comp. Sci.) 2011, 77-88.
5. Capobianco, Silvio, and Tommaso Toffoli, "Dissipative CA computation without power sources?" *J Cellular Automata* **5** (2010), 169–183.
6. Toffoli, Tommaso, Postscript to "Challenges in cellular automata theory" (Andrew Adamatzky et al), *J Cellular Automata* **5** (2010), 405–407.
7. Toffoli, Tommaso, "Conceptual background for the quad Prize," *J Cellular Automata* **5** (2010), 409–414
8. Toffoli, Tommaso, "Lattice-gas vs cellular automata: the whole story at last," *J Cellular Automata* **4** (2009), 267–292.
9. Levitin, B Lev, and Tommaso Toffoli, "The fundamental limit on the rate of quantum dynamics: the unified bound is tight," *Phys. Rev. Lett.* **103**, 160502 (2009).
10. Toffoli, Tommaso, Silvio Capobianco, and Patrizia Mentrasti, "When—and how—can a cellular automaton be rewritten as a lattice gas?" *Theoretical Computer Science* **403** (2008), 71–88.
11. Levitin, B Lev, and Tommaso Toffoli, "Thermodynamic cost of reversible computing," *Phys. Rev. Lett.* **99** (2007), 110502.
12. Levitin, Lev B., and Tommaso Toffoli, "Information between quantum systems via povms," *Int. J Theor. Phys.* **44**:11 (Nov 2005), 1987–1992.
13. Levitin, Lev, Tommaso Toffoli, and Zac Walton, "Information and distinguishability of ensembles of identical quantum states," *Int. J Theor. Phys.* **44** (2005), 965–970.
14. Levitin, Lev, Tommaso Toffoli, and Zac Walton, "Maximum speed of quantum gate operation," *Int. J Theor. Phys.* **44** (2005), 965–970.
15. Toffoli, Tommaso, "Nothing makes sense in computing except in the light of evolution," *Int. J Unconventional Computing* **1** (2004), 3–29. Lead article in the premiere issue.
16. Toffoli, Tommaso, Patrizia Mentrasti, and Silvio Capobianco, "A new inversion scheme, or how to turn second-order cellular automata into lattice gases," *Theor. Comp. Sci.* **325** (2004), 329–344.

17. Toffoli, Tommaso, "Honesty in inference," review of ET Jaynes' book *Probability Theory: The Logic of Science*, in *Am. Scientist* **92** (2004), 182–185.

18. Toffoli, Tommaso, "A pedestrian's introduction to spacetime crystallography," *IBM J Res. Devel.* **48**:1 (Jan 2004), 13–29.

19. Toffoli, Tommaso, "A digital perspective and the quest for substrate-universal behavior," *Int. J Theor. Phys.* **42** (2003), 147–151.

20. Toffoli, Tommaso, "On a plucked string," *College Math. J* **34** (2003), 390–393.

21. Toffoli, Tommaso, "What is the Lagrangian counting?" *Int. J Theor. Phys.* **42** (2003), 363–381.

22. Toffoli, Tommaso, "How much is used punched tape worth?", submitted to *Mathematical Magazine*, requested revisions in progress.

23. Toffoli, Tommaso, and Ted Bach, "A common language for 'programmable matter' (cellular automata and all that)," *AI*IA Notizie* (Bulletin of the Italian Artificial Intelligence Association) **14**:2 (Jun 2001), 32.

24. Toffoli, Tommaso, "Self-powered dummy loads check out multiple power supplies," *Electronic Design* **48**:8 (17 Apr 2000), 118–120.

25. Toffoli, Tommaso, "Programmable matter methods," *Future Generation Computer Systems* **16** (1999), 187–201

26. Toffoli, Tommaso, "*Quo vadimus?*—Much hard work is still needed," *Physica D* **120** (1998), 1–11.

27. Kotiuga, Robert, and Tommaso Toffoli, "Potential for computation in micromagnetics via topological conservation laws," *Physica D* **120** (1998), 139–161.

28. Toffoli, Tommaso, "How much physics is *just* computation?" *Superlattices and Microstructures* **23** (1998), 381–406.

29. Toffoli, Tommaso, and Jason Quick, "Three-dimensional rotations by three shears," *Graphical Models and Image Processing* **59** (1997), 89–96.

30. Toffoli, Tommaso, "Almost every unit matrix is a ULU," *Linear Algebra and Its Applications* **259** (1997), 31–38.

31. Toffoli, Tommaso, "Occam, Turing, von Neumann, Jaynes: How much can you get for how little? (A conceptual introduction to cellular automata)," *The Interjournal* (October 1994).

32. Toffoli, Tommaso, and Margolus, Norman, "Programmable matter," *Int. J High Speed Computing* **5** (1993), 155–170.

33. Toffoli, Tommaso, review of *Complex System Dynamics* (G Weisbuch), *Am. Scientist* **80** (1992), 500-501.

34. Smith, Mark, Yaneer Bar–Yam, Y Rabin, B Ostrovsky, S Glotzer, H Stanley, C Bennett, N Margolus, and T Toffoli, "Parallel Processing Simulation of Polymers," in *Computational Polymer Science* 1992.

35. Toffoli, Tommaso, and Margolus, Norman, "Programmable matter," *Physica D* **47** (1991), 263–272.

36. Toffoli, Tommaso, and Norman Margolus, "Invertible Cellular Automata: A Review," *Physica D* **45** (1990), 229–253.

37. Bennett, Charles H, Norman Margolus, and Tommaso Toffoli, "Bond-energy variables for Ising spin-glass dynamics," *Phys. Rev. B* **37** (1988), 2254.

38. Toffoli, Tommaso, "Information Transport Obeying the Continuity Equation," *IBM J Res Develop* **32**:1 (Jan. 1988), 29–36.

39. Toffoli, Tommaso, Norman Margolus, and R Fiorini, "Macchine ad automi cellulari," *PIXEL* **8**:9 (Sep 1987), 23–32.

40. Margolus, Norman, and Tommaso Toffoli, "Cellular Automata Machines," *Complex Systems* **1** (1987), 967–993.

41. Margolus, Norman, Tommaso Toffoli, and Gérard Vichniac, "Cellular-automata supercomputers for fluid-dynamics processing," *Phys. Rev. Lett.* **56** (1986), 1694–1696.

42. Toffoli, Tommaso, "Comment on 'Dissipation in Computation'," *Phys. Rev. Lett.* **53** (1984), 1204.

43. Toffoli, Tommaso, "Cellular automata as an alternative to (rather than an approximation of) differential equations in modeling physics," *Physica D* **10** (1984), 117–127.

44. Toffoli, Tommaso, "cam: A high-performance cellular-automaton machine," *Physica D* **10** (1984), 195–204.

45. Fredkin, Edward, and Tommaso Toffoli, "Conservative Logic," *Int. J Theor. Phys.* **21** (1982), 219–253. Reprinted in *Collision Based Computing* (Andrew Adamatzky ed.), Springer 2002, 47–81.

46. Toffoli, Tommaso, "Physics and Computation," *Int. J Theor. Phys.* **21** (1982), 165–175.

47. Pallottino, Stefano, and Tommaso Toffoli, "An efficient algorithm for determining the length of the longest dead path in a lifo branch-and-bound exploration schema," *ACM Trans. Math. Software* **7** (1981), 498–504.

48. Toffoli, Tommaso, "Bicontinuous extension of reversible combinatorial functions," *Math. Syst. Theory* **14** (1981), 13–23.

49. Pallottino, Stefano, and Tommaso Toffoli, "PREMPS: A precompiler for large, multiperiod linear-programming models," *Informatica* **7**:1 (Jan–Mar 1977), 39–53.

50. Toffoli, Tommaso, "Computation and construction universality of reversible cellular automata," *J Comp. Syst. Sci.* **15** (1977), 213–231.

Book chapters; refereed proceedings; encyclopedias articles

1. Levitin, Lev B, and Tommaso Toffoli, "Information retrievable from an image in natural light," *Advances in Computing, Communications, & Information* (4th IEEE ICACCI conference), 2015.

2. Capobianco, Silvio, and Tommaso Toffoli, "Can anything from Noether's theorem be salvaged for discrete dynamical systems?" in "Proc. 10th Int. Conf. Unconventional Computation 2011" (Turku, Finland, June 6–10), Springer (*Lecture Notes in Computer Science*) 2011, 77-88.

3. Toffoli, Tommaso, "Probability is a lot of logic at once: if you don't know which case to pick, take 'em all)," lead chapter of *Randomness through Computation* (H Zénil ed.), World Scientific 2010, 27–47.

4. Calude, CS, Gregory Chaitin, Edward Fredkin, T Leggett, R de Ruyter, Tommaso Toffoli, and Stephen Wolfram, "What is computation? (How) does nature compute?" (panel discussion), in *Randomness through Computation* (H Zénil ed.), World Scientific 2010, 255–298.

5. Toffoli, Tommaso, "Foreword" to *Simulating Complex Systems by Cellular Automata* (Alfons Hoekstra et al., ed.), Springer 2010.

6. Levitin, Lev B, and Tommaso Toffoli, "The unified bound on the rate of quantum dynamics," in *Quantum Communication Measurement and Computing (QCMC'08)*, Am. Inst. Physics 2010, 13–16.

7. Levitin, Lev B, and Tommaso Toffoli, "Energy dissipation in reversible computing," in *Quantum Communication, Measurement and Computing*, (O Hirota, JH Shapiro, and M Sasaki, eds.), NICT Press 2007, 125–128.

8. Levitin, Lev, and Tommaso Toffoli, "Thermodynamical cost of reversible computing," *2006 IEEE Int. Symp. on Information Theory*, IEEE 2006 (ISBN: 1-4244-0504-1), 2082–2084.

9. Toffoli, Tommaso, "Foreword" to Gregg Jaeger's *Quantum Information: An overview*, Springer 2006, 3–5.

10. Toffoli, Tommaso, and Lev B Levitin, "Specific ergodicity: An informative indicator for invertible computational media," *Computing Frontiers '05*, ACM 2005, 52–58.

11. Levitin, Lev B, and Tommaso Toffoli, "Thermodynamical cost of reversible computing," *Computing Frontiers '05*, ACM 2005, 445–446.

12. Toffoli, Tommaso, "Cellular automata," *Encyclopedia of Physics* (Rita Lerner and George Trigg eds.), 3rd edition, Wiley–VCH 2005, 258–261.

13. Toffoli, Tommaso, "Computation: The lego of physics," in *TRG: On Transient Realities and Their Generators*, FoAM (in close cooperation with "Time's Up," Austria, and "Kibla," Slovenia), Brussels 2006, Linz 2005, ISBN: 9081073338, 130–180.

14. Toffoli, Tommaso, and Lev B Levitin, "Specific ergodicity: An informative indicator for invertible computational media," in *First Int. Workshop of Reversible Computing*, ACM Computing Frontiers conference, Ischia, Italy, 4–6 May 2005.

15. Levitin, Lev B, and Tommaso Toffoli, "Thermodynamical cost of reversible computing," in *First Int. Workshop of Reversible Computing*, ACM Computing Frontiers conference, Ischia, Italy, 4–6 May 2005.

16. Levitin, Lev B., and Tommaso Toffoli, "Mutual information in quantum systems," in *Quantum Communication, Measurement, and Computing*, (Stephen Barnett, Osamu Hirota, et al. ed.), Am. Inst. Physics 2004, 29–31.

17. Bach, Ted, and Tommaso Toffoli, "simp/step: A rational framework for 'crystalline computing' (cellular automata, lattice gases, and the like)", SCI2003 Proceedings (Seventh World Multiconference on Systemics, Cybernetics and Informatics, Orlando FL, 27–30 Jul 2003).

18. Toffoli, Tommaso, Silvio Capobianco, and Patrizia Mentrasti, "Structural vs functional invertibility in computation," Simons Conference on Quantum and Reversible Computation, Stony Brook, 28–31 May 2003.

19. Levitin, Lev, Tommaso Toffoli, and Zac Walton, "Operation time of quantum gates," in *Quantum Commmunication, Measurement and Computing* (J Schapiro and O Hirota, eds.), Rinton 2003, 457–459.

20. Toffoli, Tommaso, "A man and his computer: An issue of adaptive fitness and personal satisfaction,"

Unconventional Models of Computation (CS Calude et al., eds.), Springer 2002, 87–99.

21. Toffoli, Tommaso, "Symbol Super Colliders," in *Collision Based Computing* (Andrew Adamatzky ed.), Springer 2002, 1–23.
22. Fredkin, Edward, and Tommaso Toffoli, "Design principles for submicron digital technologies" (from a seminal 1978 darpa proposal), in *Collision Based Computing* (Andrew Adamatzky ed.), Springer 2002, 27–46.
23. Levitin, Lev B., Tom Toffoli, and Zac *Walton*, "Information and distance in Hilbert space," in *Quantum, Communication, Measurement and Computing 3* (O Hirota and P Tombesi, eds.), Kluwer Academic/Plenum Publishers 2001, 19–25.
24. Toffoli, Tommaso, "Non-conventional computers," *Wiley Encyclopedia of Electrical and Computer Science* vol. 14 (JG Webster ed.), Wiley 1998, 455–471.
25. Toffoli, Tommaso, "What you always wanted to know about genetic algorithms but were afraid to hear," *Festschrifts in honor of John Holland*, (Lashon Booker, Stephanie Forrest, Melanie Mitchell, and Rick Riolo, ed.), Center for the Studies of Complex Systems, The Univ. of Michigan, Jun 1999, 131–136.
26. Benigni, Andrea, Patrizia Mentrasti, and Tommaso Toffoli, "A model of urban transport simulation using the cellular automata machine cam8," in *Automata '99* (Marianne Delorme and Jacques Mazoyer, eds.), ENS Lyon, France, Oct 1999, 9–10.
27. Toffoli, Tommaso, "Action, or the fungibility of computation," *Feynman and Computation: Exploring the limits of computers* (Anthony Hey ed.), Perseus 1998, 348–392.
28. Toffoli, Tommaso, "Power management alternatives for nanoscale cellular automata," in *PhysComp96* (Toffoli, Tommaso, Michael Biafore, and João Leão, eds.), New England Complex Systems Institute 1996, 304–309.
29. Toffoli, Tommaso, "Cellular automata," *The Handbook of Brain Theory and Neural Networks* (Michael Arbib, ed.), MIT Press 1995, 166–169.
30. Toffoli, Tommaso, "Fine-grained models and massively-parallel architectures: the case for programmable matter," in *Proc. Seventh SIAM Conference on Parallel Processing for Scientific Computing* (DH Bailey et al., eds.) 1995, 195–200.
31. Toffoli, Tommaso, "Neural Networks," *Encyclopedia of Applied Physics*, 2nd edition (Lerner and Trigg ed.) VCH Publ 1994, 275–296.
32. Toffoli, Tommaso, "Occam, Turing, von Neumann, Jaynes: How much can you get for how little? (A conceptual introduction to cellular automata)," *ACRI '94: Automi Cellulari per la Ricerca e l'Industria*, Rende, Italy, 29–30 Sep 1994.
33. Ostrovsky, S, M Smith, M Biafore, Y Bar–Yam, Y Rabin, N Margolus, and T Toffoli, "Massively parallel architectures in polymer simulation," in Proc. 6th SIAM Conf. on *Parallel Processing for Scientific Computing*, SIAM 1993, 193–202.
34. Toffoli, Tommaso, "What are nature's 'natural' ways of computing?" in *Workshop on Physics and Computation—PhysComp '92*, IEEE Computer Society Press 1993, 5–9.
35. Smith, Mark, Yaneer Bar–Yam, Y Rabin, N Margolus, T Toffoli, and CH Bennett, "Cellular automaton simulation of polymers," in *Complex Fluids* (D Weitz *et al.*, eds.), Materials Research Society 1992, 483–488.
36. Toffoli, Tommaso, "Cellular automata," *Encyclopedia of Physics*, VCH Publ. 1991, 126–127.
37. Margolus, Norman, and Tommaso Toffoli, "Cellular Automata Machines," in *Lattice Gas Methods for Partial Differential Equations* (Gary Doolen ed.), Addison–Wesley 1990, 219–248.
38. Toffoli, Tommaso, "How cheap can mechanics' first principles be?" *Complexity, Entropy, and the Physics of Information* (WH Zurek ed.), Addison–Wesley 1990, 301–318.
39. Toffoli, Tommaso, "Frontiers in Computing," in *Information Processing* (GX Ritter ed.), North–Holland 1989, 1.
40. Toffoli, Tommaso, "Four topics in lattice gases: Ergodicity; Relativity; Information flow; and Rule compression for parallel lattice-gas machines," in *Discrete Kinetic Theory, Lattice Gas Dynamics and Foundations of Hydrodynamics* (R Monaco ed.), World Scientific 1989, 343–354.
41. Toffoli, Tommaso, "Cellular automata machines as physics emulators," in *Impact of Digital Microelectronics and Microprocessors on Particle Physics* (M Budinich et al., eds.), World Scientific 1988, 154–160.
42. Toffoli, Tommaso, "Pattern recognition and tracking by texture-locked loops," in *Advanced Computer Architectures for Robotics and Machine Intelligence: Neural Networks and Neurocomputers*, IEEE 1987.
43. Toffoli, Tommaso, "Reversible Computing," in *Automata, Languages and Programming* (de Bakker and van Leeuwen, eds.), Springer–Verlag

1980, 632–644. Adapted and condensed version of an MIT technical report of the same title.

44. Toffoli, Tommaso, "The role of the observer in uniform systems," in *Applied General Systems Research* (George Klir ed.), Plenum 1978, 395–399.

45. Toffoli, Tommaso, "Integration of the phase-difference relations in asynchronous sequential networks," in *Automata, Language, and Programing* (G Ausiello and C Bohm, eds.), Springer–Verlag 1978, 458–463.

46. Pallottino, Stefano, and Tommaso Toffoli, "Modelizzazione di bacini idrografici: Un sistema interattivo per la costruzione e il trattamento di modelli," in *Applicazioni del Calcolo—Scritti offerti a Mauro Picone nel suo 90° compleanno* (Ilio Galligani ed.), Veschi, Roma 1975, 157–171.

47. Martino, Enrico, Bruno Simeone, and Tommaso Toffoli, "An automatic river planning operating system (ARPOS)," in *Fifth Conference on Optimization Techniques, Part II*, Springer 1973, 241–250.

Papers in other proceedings

1. Toffoli, Tommaso, "Renaissance man: cvi bono? Charting a path from hands-on learning to literate design," Creating the New Humanist in University Undergraduate Education, 18 Apr 2008, a Boston University campus conference sponsored by the Associate Provost for Undergraduate Education.

2. Toffoli, Tommaso, "Programmable matter: a laboratory for learning what goes into creation," in Proc. 2nd Int. Symp. on *Conceptual Tools for Understanding Nature*, Univ. Trieste, Sep. 1992.

3. Pallottino, Stefano, and Tommaso Toffoli, "Construction and manipulation of large data structures by means of in-house minicomputer having access to a remotely-connected large computer," in *Contributions of Nuclear Physics Research to the Development and Diffusion of Computer Science Techniques*, Bari, Italy, 1975.

Translations

1. Gagné, Robert, *Apprendimento e differenze individuali* (translated from *Learning and Individual Differences*, Merrill 1967), Armando Editore, Roma 1974, 366pp.

White papers, Arxiv papers, theses, tech reports

1. Walton, Zachary, McNamara, Bernard, and Toffoli, Tommaso, "Quantum mechanics as naturalized time," ArXiV:2004.12052.

2. Levitin, B Lev, and Tommaso Toffoli, "Work recoverable from two-particle information," `arXiv:1101.1325v1` [quant-ph] 6 Jan 2011.

3. Toffoli, Tommaso, "Thermodynamics of used punched tape: A weak and a strong equivalence principle," `arxiv.org/cs.IT/0501046`.

4. Levitin, Lev B, and Tommaso Toffoli, "Information between quantum systems via povms," `arxiv.org/quant-ph/0306058`.

5. Toffoli, Tommaso, "Maxwell's daemon, the Turing machine, and Jaynes' robot," review of ET Jaynes' book *Probability Theory: The Logic of Physics*, `arxiv.org/math.PR/0410411`. An adaptation of this review appeared, under the title "Honesty in inference," in *Am. Scientist* **92** (2004), 182–185.

6. Walton, Zac, and Tommaso Toffoli, "On the impossibility of instantaneous communication," e-paper.

7. Toffoli, Tommaso, "Knowledge Structuring: The substance of information technology," course syllabus, Turin, Italy 2000.

8. Toffoli, Tommaso, "Three-dimensional interconnect having stacking modules with orthogonal geometry," Tech. Rep. 97-004 (March 1997), Boston Univ. ECE Dept.

9. Toffoli, Tommaso, "Ballistic computation: ideal and critique," pre-print, delivered at the Joint Spring Meeting of the New York State Section of the American Physical Society and the American Association of Physics Teachers, 12 Apr 1996.

10. Toffoli, Tommaso, "Fine-Grained Parallel Supercomputer," Tech. Rep. PL-TR-95-2013, Phillips Laboratory, Hanscom AFB, Department of Defense, Nov 1994, 197+viii pp.

11. Agin, Ruben, Michael Biafore, Raissa D'Souza, Surya Ganguli, Harris Gilliam, Norman Margolus, Pierluigi Pierini, Jason Quick, Daniel Risacher, Mark Smith, Tommaso Toffoli, and Jeffrey Yepez, "An early sampler of cam8 applications," Tech. Memo MIT/LCS/TM-513, MIT Lab. for Comp. Sci. (Oct. 1994).

12. Margolus, Norman, and Tommaso Toffoli, *STEP1: A SpaceTime Event Processor*, a technical handbook for the cam8 architecture, 1993.

13. Toffoli, Tommaso, "Analytical mechanics from statistics: $T = dS/dE$ holds for almost any system," Tech. Memo MIT/LCS/TM-407, MIT Lab. for Comp. Sci., Aug 1989.
14. Margolus, Norman, Tommaso Toffoli, Charles H Bennett, Gérard Vichniac, Mark Smith, and Andrea Califano, cam*6 Software*, Systems Concepts, San Francisco CA 1984, 1987; *CAM-PC Software*, Automatrix Inc., Rexford, NY 1991.
15. Toffoli, Tommaso, and Norman Margolus, "The cam7 Multiprocessor: A Cellular Automata Machine," Tech. Memo MIT/LCS/TM-289, MIT Lab. for Comp. Sci., Dec 1985.
16. Sagüés, Alberto, and Tommaso Toffoli, "Applications of cellular automaton model to the prediction of solid particle erosion patterns," *Erosion, Wear, and Corrosion*, TMS-AIME, Alberta, Oct 1985.
17. Toffoli, Tommaso, "Reversible Computing," Tech. Memo MIT/LCS/TM-151, MIT Lab. for Comp. Sci., Feb 1980.
18. Pallottino, Stefano, and Tommaso Toffoli, "Il sistema PREMPS: descrizione e manuale d'uso," *Quaderno III-24*, Istituto per le Applicazioni del Calcolo, CNR, Roma 1977.
19. Toffoli, Tommaso, "Cellular Automata Mechanics," *PhD Thesis*, The Univ. of Michigan, Comp. Comm. Sci. Dept. 1977; and *Tech. Rep. No. 208*, Logic of Computers Group (1977), 259 pp. Published as *AAT 7804823* Source: DAI-B 38/11, p. 5479, May 1978. ProQuest document ID: 758535201.
20. Toffoli, Tommaso, "River planning with ARPOS: An overview," *Quaderno III-23*, Istituto per le Applicazioni del Calcolo, CNR, Roma 1976.
21. Toffoli, Tommaso, "On the large-scale implementation of cellular automata by means of integrated-circuit arrays," *Tech. Rep.*, Istituto per le Applicazioni del Calcolo, CNR, Roma 1972.
22. Toffoli, Tommaso, "Studio e realizzazione di un rivelatore direzionale di raggi cosmici a luce di Čerenkov," *Doctoral Thesis*, Univ. Roma, Istituto di Fisica, 1967.

Conference talks (selection)

1. Levitin, Lev B, and Tommaso Toffoli, "Heat-to-work conversion by exploiting quantum correlations," 10th Conference on Quantum Structures, QS2010, Boston, Jun 2010.
2. Levitin, Lev B, and Tommaso Toffoli, "Work recoverable from two-particle information," 10th Int. Conf. on Quantum Communication, Measurement and Computing, QCMC 2010, Brisbane, Australia, Jul 2010.
3. *Toffoli*, Tommaso, "Computing for capitalists? Life without batteries and other Faustian bargains," NKS Midwest Conference, 1 Nov 2008.
4. *Toffoli*, Tommaso, "Lattice gases vs cellular automata: the whole story at last," Automata 2008—Theory and applications of cellular automata, Bristol, Jun 2008.
5. Capobianco, Silvio, and Tommaso Toffoli, "Dissipative CA computation without power sources?" Automata 2008—Theory and applications of cellular automata, Bristol, Jun 2008.
6. *Toffoli*, Tommaso, "Renaissance man: cvi bono? Charting a path from hands-on learning to literate design," Creating the New Humanist in University Undergraduate Education, 18 Apr 2008, a Boston University campus conference sponsored by the Associate Provost for Undergraduate Education.
7. Levitin, Lev, and Tommaso *Toffoli*, "A generalized bound on the rate of quantum dynamics," 9th Int. Conf. on Quantum Communication, Measurement, and Computing, Calgary, Canada, Aug 2008.
8. Levitin, Lev B, and Tommaso Toffoli, "Orthogonalization time revisited," The 9th Conference on Quantum Structures, QS2008, Sopot, Poland, Jul 2008,
9. Levitin, Lev, and Tommaso Toffoli, "Energy dissipation in reversible computing," *The 8th Int. Conf. on Quantum Communication, Measurement, and Computing*, Tsukuba, Japan, Dec 2006.
10. Levitin, Lev, and Tommaso Toffoli, "Thermodynamical cost of reversible computing," *2006 IEEE Int. Symp. on Information Theory*, Seattle, July 2006.

Invited lectures (selection)

1. *Toffoli*, Tommaso,"What is Computation? (How) Does Nature compute?" Panel discussion, NKS Midwest Conference, 2 Nov 2008
2. *Toffoli*, Tommaso, "A Knowledge Home: A culture for extending literacy by the computer," Informatics Seminar, University of Reykjavik, 16 Jun 2008.
3. *Toffoli*, Tommaso, "The ultimate cost of conformal computing," Avogadro-scale computing workshop, Center for Bits and Atoms, Media Lab, MIT, 17 Apr 2008.
4. "Simple things work best: Computing with gases, qubits, and emergent phenomena," Lockheed Martin Co., Philadelphia, 5 Jun 2006.

5. "The question they all ask: How do you make up a rule to give a desired behaviour?" FENA Workshop on Computation in Nanoscale Dynamical Systems, Santa Fe NM, 19–20 January 2006.
6. "Computation: The LEGO of physics," Data Ecologies Workshop, Time's Up, Linz 13–14 May 2005.
7. "Realistic and elusive prospects: A critical overview of current trends in computation," 2005 Chief Scientist Lecure Series, Air Force Laboratory, Rome NY, 25 May 2005.
8. "What kind of batteries does a quantum computer run on?" Symposium on Quantum Technologies for the 21st Century, ELSAG, Genoa 2004.
9. "Von Neuman's century: Too many souls," keynote speech, ACRI conference, Amsterdam 2004.
10. "All roads lead to Rome—if Rome is big enough," Workshop on Understanding Complexity in Natural, Technological and Social Systems, School of Engineering and Applied Science, Princeton 2003.
11. "Structural vs functional invertibility in computation," Simons Conference, Stony Brook 2003.
12. "Achieving information assurance," Shafer Corporation, Washington 2003.
13. "How much is left to be done in complexity?" Brainstorming meeting on Complex Systems, European Committee Planning Session, Brussels 2002.
14. "A man and his computer," keynote speech, Unconventional Models of Computation conference, Kobe, Japan 2002.
15. "Eusocial vs eukaryotic perspectives in the evolution of the human individual," Institute for Scientific and Techonological Research, Trento, Italy 2002.
16. "Adiabatic charge transfer: from diffusive to ballistic computing," 2001.
17. "From deep structure to surface representation: the servo loop that powers art and science," Expanding Perceptions symposium, I.S.I. Foundation, Turin, Italy, 2001.
18. "What you always wanted to know about genetic algorithms but were afraid to hear," Festschrifts symposium in honor of John Holland, Center for the Studies of Complex Systems, The Univ. of Michigan, Ann Arbor MI, 1999.
19. "Knowledge Engineering," Boston Univ. ECE Seminar, Boston 1999.
20. "How to make a book (or a technical paper) with the help of a computer, " Math. Dept. Colloquium, Univ. Rome "La Sapienza," Rome 1998.
21. "How much of physics is just computation?" Boston Univ. Comp. Sci. Colloq., 1997.
22. "Ballistic computation: ideal and critique," Joint Spring Meeting of the New York State Section of the Am. Phys. Soc. and the Am. Assoc. Phys. Teachers, 12 Apr 1996.
23. "Programmable Matter," Am. Phys. Soc. meeting, San Francisco 1995.
24. "Occam, Turing, Jaynes, or How much can one get for how little? (an introduction to cellular automata)," Electronic Research Laboratory, MIT 1994.
25. "Programmable Matter," Harvard Phys. Dept. Colloq., 1994.
26. "Computational Architectures at the Nanoscale," Los Alamos National Laboratory 1993.
27. "Programmable matter: a laboratory for learning what goes into creation," *Conceptual Tools for Understanding Nature*, Univ. Trieste 1992.
28. "Programmable Matter," Argonne National Laboratories, 1990.
29. "Cellular automata as computational accessible models of physics," Condensed Matter and Radiation Sciences Division, Naval Res. Lab., Washington DC 1989.
30. "Cellular automata and cellular automata machines," TASC presentation, Washington DC 1988.
31. "Relativity in computation," Laboratory for Computer Science seminar, MIT 1988.
32. "Texture-locked loops: Long-range optimization by local mechanisms," Advanced Computer Architectures for Robotics and Machine Intelligence, IEEE panel, Raleigh NC 1987.